Measurement of Total Ion Flux in Vacuum Arc Discharges

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Abstract – **A vacuum arc ion source was modified allowing us to collect ions from arc plasma streaming through an anode mesh. The mesh had a geometric transmittance of 60%, which was taken into account as a correction factor. The ion current from twenty-two cathode materials was measured at an arc current of 100 A. The ion current normalized by the arc current was found to depend on the cathode material, with values in the range from 5% to 11%. The normalized ion current is generally greater for light elements than for heavy elements. The ion erosion rates were determined from values of ion current and ion charge states, which were previously measured in the same experimental system. The ion erosion rates range from 12-94 μg/C.**

I. Introduction

Cathodic arc discharge phenomena have been investigated for more than 200 years [1-3]. Many investigators have shown that the basic processes of plasma formation of cathode material occur at non-stationary cathode spots [4-8]. Cathode spots are highly dynamic, self-organized structures. For rough orientation, the following characteristic parameters are given: ignition and explosive time 1-10 ns, spot "lifetime" 10-100 ns, spot size ~ 1 μm, current density ~ 10^{12} A/m^2, and plasma density before expansion at least 10^{26} m^{-3}. The main difficulties of arc spot research are associated with these extreme parameters, and therefore a number of phenomena are still subject of research.

Measurements of the total ion flux generated in the vacuum arc plasma are important for fundamental and practical reasons. First, such data are relevant to build and test theories of vacuum arc discharges. The ion erosion rate, γ_i, which is an important parameter, can be determined from ion flux measurements. Second, for further development of vacuum arc ion sources and cathodic arc deposition equipment one needs to know the maximum value of ion current that can be extracted from the vacuum arc plasma.

The ion erosion rate can be determined based on measurements of the total ion current, I_i, the arc current, I_{arc}, and mean ion charge state $\overline{Q_i}$, as follows:

$$\gamma_i = \frac{I_i}{I_{arc}} \cdot \frac{M_i}{e\,\overline{Q_i}} = \alpha_i \cdot \frac{M_i}{e\,\overline{Q_i}}, \qquad (1)$$

where M_i is the atomic mass of the cathode material and e is elementary charge. In (1), the normalized ion current $\alpha_i = I_i / I_{arc}$ was introduced, and therefore we have a relation between ion erosion rate (usually in μg/C) and ion current (usually in % of arc current).

Pioneering work in determining ion erosion rates was done by Plyutto and co-workers [9] and a few years later by Kimblin [10, 11].

Kimblin used an arc system with pulse duration in the range 0.1-4.5 s and arc current of 50-1000 A. He determined the ion erosion rates by two methods: one is based on measuring ion currents to ion collectors, and the other is based on weighing the cathode before and after its use. The methods result in data for α_i and γ_i, which are related by equation (1). Using published data for mean ion charge states [9, 12], Kimblin [10, 11] realized that the results by these two methods are not consistent unless a significant fraction of mass loss is neutral. Kimblin reconciled the results assuming that evaporation of atoms must have occurred. With this assumption he could determine the fractional ionization of eroded cathode material, finding 15% for cadmium at the low end and 90% for molybdenum at the high end. Referring to work by Udris [13], Kimblin [10] correctly noted that vacuum arc erosion also includes macroparticles, and therefore his values "should be regarded as lower limits to the fractional ionization."

Considering *distributions* of ion charge states [14], one can quickly realize that the degree of ionization must be very high for practically all cathode elements. For example, the fraction of neutrals in cadmium arc plasmas was calculated to only 2.3%, and to 4.1 x 10^{-4} % for molybdenum [15].

The discrepancy between the ion collection and weighing methods clearly points to the contribution of macroparticles to cathode erosion. It has been shown that macroparticle mass losses are indeed important [16, 17]. Experimental results by Daalder [16] and others (e.g. Table I in [17]) show that the mass of cathode material removed by the macroparticles flux is about the same order of or even greater than the mass of cathode material leaving in form of

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ions.

Besides ion current measurements, Daalder [16, 18] also used the weighing method to determine the erosion rate of several cathode materials. From the analysis of the erosion rate as a function of charge transferred by the vacuum arc, Daalder concluded that the total erosion rate approaches the ion erosion rate if the charge transferred by the arc is small. In other words, losses by macroparticles are less important if $\int I_{arc} dt$ is kept small. Based on the assumption that the ratio of ion to arc current equals 0.1, Daalder [18] calculated the ion erosion rate for fourteen cathode materials using values of mean ion charge state published in [9, 12].

Mesyats has shown that the basic processes in cathode spots of vacuum arcs are similar to processes in vacuum breakdown and vacuum sparks; all can be based on the "ecton" concept [7, 19]. An ecton can be seen as minimum number of electrons involved in the explosive electron emission process [20, 21], hence the ecton is like a "quantum of discharge" for vacuum discharges. It is impossible for a cathode spot to exist with emission of electrons of less than one ecton. The ecton concept allows explanation of some basic characteristics of the vacuum arc. Mesyats and Barengol'ts [22] presented a calculation of ion erosion rates based on the ecton theory. Using only parameters of the cathode material and mean ion charge states from different publications as input parameters, and assuming α_i= 0.1, they found good agreement between their results and experimental erosion rates by Daalder [18].

In the present work, ion currents are measured in the same system that was previously used for measurements of ion charge state distributions [14, 23]. Combining measurements in one system allows us to produce ion erosion data in a coherent manner. In the measurements of the ion erosion rate γ_i and normalized ion current (i.e., the ratio α_i), much attention was paid to geometry effects and corrections for losses at the anode. Cathode spots occurred on a cathode surface that is cleaned by the arc as it operates, and hence results apply to a situation where the arc operates with type 2 spots, and non-metallic plasma contributions are negligible [23].

II. Experimental

The experiments were performed using the vacuum arc ion source "Mevva V" at Lawrence Berkeley National Laboratory. The source has been described elsewhere [14]; here we describe only the procedure for the ion erosion rate experiments. One reason for choosing the ion source facility was that for analysis of vacuum arc phenomena we can to directly integrate the erosion rate data with other data obtained on the same facility, such as ion charge state distribution [14], electron temperature [15], directed ion velocity [24], and burning voltage [25].

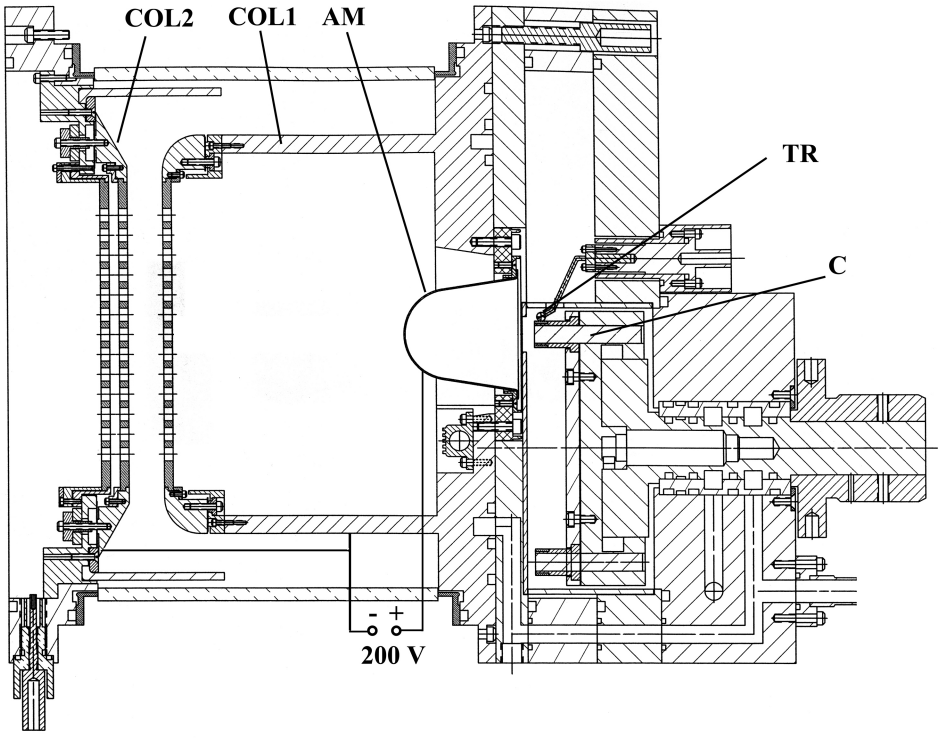

Fig. 1 Experimental setup: Modified vacuum arc ion source "Mevva V" with cathode rod "C," trigger "TR," anode mesh "AM," and the two connected collector electrodes "COL1" and COL2" (COL1 and COL2 were originally part of the ion extraction system used for charge state measurements).

The design of the ion source "Mevva V" was modified as shown in the Fig.1. Cathode spots of a vacuum arc were ignited on the front surface of a rod cathode "C". The original anode was replaced by a "transparent" anode made from fine stainless steel mesh. The mesh was spherical in shape with mesh openings of 0.8 mm x 0.8 mm and geometric transparency of 60%. The mesh anode "AM" was electrically insulated from the original ion source anode and the extraction system.

Both electrode "COL1" and "COL2" were negatively biased up to U_b = -200 V with respect to the mesh anode "AM" and therefore both electrodes served as a large ion collector to accept all ions coming through the anode mesh. During an arc pulse, the -200 V bias voltage dropped less than 10 V at the maximum observed ion current. When bias

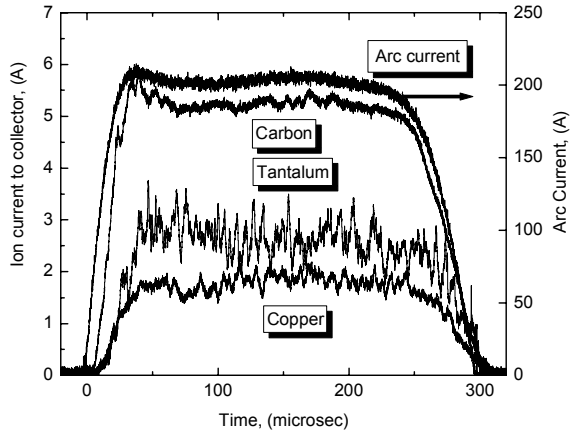

Fig. 2. Example of arc current pulse, and carbon, copper and tantalum ion currents collected by the ion-collecting electrodes

voltage was applied, ions of the plasma flowing through mesh holes were collected by the entire surface of electrodes COL1 and COL2. Ion saturation was checked by varying the bias voltage; the ion current did not change more than 5% when the bias voltage was increased from -100 V to -200 V. All further ion flux measurements were made with U_b = -200 V. This value of U_b is certainly sufficient for reflection of plasma electrons but still low to not generate many secondary electrons.

The standard electrical circuit for the arc supply of the ion source was used. An eight-stage pulse-forming-network provided arc pulses of 250 μs duration, constant (but adjustable) current amplitude up to 300 A, with a repetition rate of several pulses per second. For most experiments the arc current was 100 A. The base pressure of the experimental system was as low as $p = 6 \cdot 10^{-7}$ Torr.

The measurements included monitoring the arc current of the cathode circuit and ion current to the collector electrodes. The signals from broad-band current transformers (Pearson™ coils) were recorded in a digital oscilloscope (TDS 744) An example of experimental data is shown in Fig. 2.

III. Results

The dependence of I_i upon I_{arc} is very close to linear. The results indicate that γ_i and α_i do not depend on the vacuum arc current for the current range investigated. The results of the ion erosion rate experiments are presented in Table I for all twenty-two different cathode materials that were investigated. The measured data were corrected for the limited transmittance of the anode mesh.

TABLE I

Normalized Ion Current and Ion Erosion Rates for 100 A arc current, and comparison with published data.

Cathode material	This Experiment		Ref. [10]	Ref. [7]	Ref. [18]
	α_i, %	γ_i, μg/C	α_i, %	γ_i, μg/C	γ_i, μg/C
C	11.3	13.5	10	13-17	…
Mg	8.3	11.7	…	19-25	15
Al	8.3	14	…	22-25	15
Ti	6.8	15.2	8.0	…	…
V	5.7	12.8	…	…	…
Cr	8.0	18.2	7.5	…	19
Fe	6.0	16.9	8.0	40-50	…
Ni	4.8	14.5	…	50	32
Co	5.0	15.3	8.0	…	…
Cu	6.8	19.3	…	35-39	…
Zn	8.2	40.0	8.0	74-76	51.1
Zr	4.8	15.9	…	…	…
Nb	6.2	18.0	…	…	…
Ag	6.0	27.8	8.0	90-108	48
Cd	5.8	43.9	8.0	128-130	79.1
In	6.2	46.8	…	…	…
Sn	6.0	41.9	…	…	72.8
Gd	4.8	32.9	…	…	…
Ta	6.3	35.5	…	…	59
W	5.0	27.1	7.0	62-90	57
Pb	5.8	67.4	…	…	120.8
Bi	5.8	94.0	…	…	168

IV. Discussion

From Table I can see that the results are in reasonable agreement with Kimblin's experimental data [10, 11]. The approximate independence of arc current is consistent with findings that increasing the arc current leads to an increase in the *number* of emission centers rather than changing the character of these centers.

From the data presented in Table I it can be seen that the normalized ion current α_i is not as independent of material as claimed in [10] and often used in other work. The values of α_i range from 4.8% (Ta, Ni) to 11.3% (C). For estimates one could use an average α_i-value of 8% keeping in mind that the actual value may be different by about 50%. In general, values of α_i for light elements are greater than for heavy metals.

The ion erosion rates γ_i in Table I assigned to Daalder [18] were slightly corrected by using the more recent mean charge states published by Brown [14]. One should note that Kimblin found a linear relationship between ion flux and arc current for DC arcs up to 3000 A. Focusing on carbon, Schülke and Anders [26] determined a slight increase of α_i by 1.2% per 100 A in the range 100 A to 1200 A. This could be in part due to a slight increase of the mean ion charge state with increasing current [27].

The ion erosion rates estimated by our measurements are lower than Mesyats' [7] and Daalder's [18] rates. Possible reasons for these differences may lie in the details and methodology of data interpretation. Although much attention was paid to use accurate correction factors, a systematic error in our measurement could be due overestimating the transmittance of the anode mesh and underestimating the loss of ions emitted under very shallow angle to the cathode surface. Another reason for the discrepancy with data presented in [7, 18] could be that in the weighing method, macroparticles might not be accurately accounted for, as discussed before.

V. Summary

The ion erosion rates for twenty-two cathode elements have been measured based on ion current measurements and ion charge state measurements made in the same system. It was found that the normalized ion current is not the "universal" constant of 0.1, as often claimed and used, but it slightly depends on the material. The range of α_i is 5.8% – 11.3%. Light elements tend to have a higher α_i than heavy elements. Using mean charge state data, ion erosion rates in the range 12-94 μg/C have been found.

Acknowledgments

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